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Study of $B \to D^{(*)} D^{(*)}_{s(J)}$ Decays and Measurement of D_s^- and $D_{sJ}(2460)^-$ Branching Fractions

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We present branching fraction measurements of twelve B meson decays of the form $B \rightarrow D^{(*)}D^{(*)}_{s(J)}$. The results are based on $\Upsilon(4S)$ decays in $B\overline{B}$ pairs. One of the B mesons is fully reconstructed and the other decays to two charm mesons, of which one is reconstructed, and the mass and momentum of the other is inferred by kinematics. Combining these results with previous exclusive branching fraction measurements, we determine $\mathcal{B}(D_s^- \rightarrow \phi\pi^-) = (4.62 \pm 0.36_{\rm stat.} \pm 0.51_{\rm syst.})\%$, $\mathcal{B}(D_{sJ}(2460)^- \rightarrow D_s^{*-}\pi^0) = (56 \pm 13_{\rm stat.} \pm 9_{\rm syst.})\%$ and $\mathcal{B}(D_{sJ}(2460)^- \rightarrow D_s^-\gamma) = (16 \pm 4_{\rm stat.} \pm 3_{\rm syst.})\%$.

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In this paper we present the study of charged and neutral B mesons decaying to two charm mesons, i.e. $\overline{B} \rightarrow D_{\rm meas}D_X$ [1]. $D_{\rm meas}$ represents a fully reconstructed $D^{(*)+,0}$ or $D_s^{(*)-}$ meson, and the mass and momentum of the D_X are inferred from the kinematics of the two-body B decay. This study allows measurements of B branching fractions without any assumption on the decays of the D_X. Measurements of these two-body branching fractions can provide tests of the factorization of the decay amplitudes [2] in the high momentum transfer regime [3]. From two separate classes of events with $D_{\rm meas} = D_s^{(*)-}$ and with $D_X = D_s^{(*)-}$ we measure the branching fraction of $D_s^- \rightarrow \phi\pi^-$, which has important implications for a wide range of D_s and B physics. Furthermore, we select final states with $D_X = D_{sJ}(2460)^-$ and combine with the *BABAR* measurements of $\mathcal{B}(\overline{B} \rightarrow D^{(*)+,0}D_{sJ}(2460)^-) \times \mathcal{B}(D_{sJ}(2460)^- \rightarrow D_s^{*-}\pi^0)$ and $\mathcal{B}(B \rightarrow D^{(*)+,0}D_{sJ}(2460)^-) \times \mathcal{B}(D_{sJ}(2460)^- \rightarrow D_s^-\gamma)$ [4], thus extracting for the first time the absolute branching fractions of this recently observed state [5].

This analysis uses $\Upsilon(4S) \rightarrow B\overline{B}$ events in which either a B^+ or a B^0 meson decays into a fully reconstructed hadronic final state ($B_{\rm reco}$). The measurements are based on an integrated luminosity of 210.5 fb^{-1} recorded at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider operating near the $\Upsilon(4S)$ resonance. An additional 21.7 fb^{-1} recorded 40 MeV below the resonance (*off-resonance*) are used to evaluate backgrounds. The *BABAR* detector is described in detail elsewhere [6]. Charged-particle trajectories are measured by a vertex tracker with 5 double-sided layers and a 40-layer drift chamber, both operating in a 1.5-T magnetic field of a superconducting solenoid. Charged-particle identification is provided by the specific energy loss (dE/dx) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector. Photons are detected by a CsI(Tl) electromagnetic calorimeter. We use Monte Carlo simulations (MC) of the *BABAR* detector based on GEANT4 [7] to optimize selection criteria and determine selection efficiencies.

To reconstruct a large sample of B mesons, the hadronic decays $B_{\rm reco} \rightarrow \overline{D}Y^+, \overline{D}^*Y^+$ are selected. Here, the system Y^+ consists of hadrons with a total charge of $+1$, composed of $n_1\pi^{\pm}\, n_2K^{\pm}\, n_3K_S^0\, n_4\pi^0$, where $n_1 + n_2 \leq 5$, $n_3 \leq 2$, and $n_4 \leq 2$. We reconstruct $D^{*-} \rightarrow \overline{D}^0\pi^-$; $\overline{D}^{*0} \rightarrow \overline{D}^0\pi^0, \overline{D}^0\gamma$; $D^- \rightarrow K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S^0\pi^-$, $K_S^0\pi^-\pi^0$, $K_S^0\pi^-\pi^-\pi^+$; $\overline{D}^0 \rightarrow K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K_S^0\pi^+\pi^-$; and $K_S^0 \rightarrow \pi^+\pi^-$. The kinematic consistency of $B_{\rm reco}$ candidates is checked with two variables, the beam energy-substituted mass $m_{\rm ES} = \sqrt{s/4 - \vec{p}_B^{\,2}}$ and the energy difference $\Delta E = E_B - \sqrt{s}/2$. Here $\sqrt{s}$ is the total energy in the $\Upsilon(4S)$ center-of-mass (CM) frame, and $\vec{p}_B$ and E_B denote the momentum and energy of the $B_{\rm reco}$ candidate in the same frame. The resolution on ΔE is measured to be $\sigma_{\Delta E} = 10 - 35\,\rm MeV$, depending on the decay mode, and we require $|\Delta E| < 3\sigma_{\Delta E}$.

For each reconstructed B decay mode, the purity $\mathcal{P}$ is estimated as the ratio of the number of signal events with $m_{\rm ES} > 5.27\,{\rm GeV}/c$ to the total number of events in the same range, and is evaluated on data. We only use modes for which $\mathcal{P}$ exceeds a decay-mode dependent threshold in the range of 9% to 24%. In events with more than one $B_{\rm reco}$ we select the decay mode with the highest purity. On average, we reconstruct one signal $B_{\rm reco}$ candidate in 0.3% (0.5%) of the $B^0\overline{B}^0$ (B^+B^-) events.

The selected sample of $B_{\rm reco}$ is used as normalization for the determination of the branching fractions. It is contaminated by $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events and by other $\Upsilon(4S) \rightarrow B^0\overline{B}^0$ or B^+B^- decays, in which the $B_{\rm reco}$ is mistakenly reconstructed from particles coming from both B mesons in the event. To significantly reduce the $e^+e^- \rightarrow q\bar{q}$ background we require the angle θ^*_{TB}, defined in the CM frame, between the thrust axis [8] of the $B_{\rm reco}$ and the thrust axis of all charged and neutral particles in the event excluding the ones that form the $B_{\rm reco}$, to satisfy the requirement $|\cos\theta^*_{TB}| < 0.7$.

On this signal-enriched sample (Fig. 1), the contributions from the background are estimated as the sum of three components: the $e^+e^- \rightarrow q\bar{q}$, the $B^0\overline{B}^0$, and the B^+B^- events. The shapes of these background distributions are taken from MC simulation. The normalization

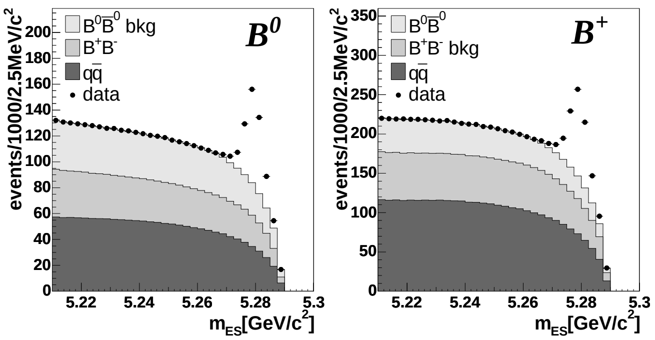

FIG. 1: Distributions in $m_{\rm ES}$ for the $B_{\rm reco}$ sample. The background contributions, determined as described in the text, are overlaid.

of the $e^+e^- \to q\bar{q}$ background is taken from *off-resonance* data, scaled by the luminosity. The normalization of the $B^0\overline{B}^0$, B^+B^- components are instead obtained by means of a χ^2 fit to the $m_{\rm ES}$ distribution in the sideband region ($5.21\,{\rm GeV}/c^2 < m_{\rm ES} < 5.26\,{\rm GeV}/c^2$). The background contamination in the signal region ($m_{\rm ES} > 5.27\,{\rm GeV}/c^2$) is extrapolated and subtracted from the data to estimate the signal yield. After correcting for the $|\cos\theta^*_{TB}|$ cut efficiency estimated in the MC, the size of the total sample of fully reconstructed B decays is $N_{B^0_{\rm reco}} = (2.90\pm0.01_{\rm stat.})\times10^5$ and $N_{B^+_{\rm reco}} = (4.63\pm0.01_{\rm stat.})\times10^5$.

From the charged tracks and the neutral clusters that do not belong to the $B_{\rm reco}$ we reconstruct the charmed mesons ($D_{\rm meas}$) in the modes $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$; $D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^0_S\pi^+$; and $D^-_s \to \phi\pi^-$ ($\phi \to K^+K^-$), $K^0_SK^-$ ($K^0_S \to \pi^+\pi^-$), and $K^{*0}K^-$ ($K^{*0} \to K^+\pi^-$). We select ϕ and K^{*0} candidates with a reconstructed mass within $15\,{\rm MeV}/c^2$ and $70\,{\rm MeV}/c^2$ from their nominal values [9], respectively. The D^* candidates are reconstructed in the decay modes $D^{*+} \to D^0\pi^+$, $D^+\pi^0$, $D^{*0} \to D^0\pi^0$, $D^0\gamma$, and $D^{*-}_s \to D^-_s\gamma$. We require the reconstructed masses of the D^0, D^+, and D^-_s candidates and the differences Δm between the masses of the D^* and D candidates to be within $1.5-3$ times its measured resolution from their nominal values [9], depending on the background level.

We apply further selection criteria to enhance the signal contributions in the sample. For $D^{(*)+}D^-_X$ and $D^{(*)-}_sD^+_X$ we consider neutral $B_{\rm reco}$ candidates while for $D^{(*)0}D^-_X$ and $D^{(*)-}_sD^0_X$ we require positive charged $B_{\rm reco}$ candidates. We suppress background from $B \to D^{(*)}l\nu$, while keeping events with a semileptonic D_X decay, by rejecting any event with a remaining identified lepton with the appropriate charge and a momentum in the B rest frame (p^*) greater than $1\,{\rm GeV}/c$. In order to minimize the contamination of the modes with a D^* to the modes with a D meson, we assign the events consistent with both the hypotheses ($B \to DD_X$ and $B \to D^*D_X$) to the D^* sample.

The invariant mass of D_X (m_X) is derived from the missing four-momentum $p_X = p_{\Upsilon(4S)} - p_{B_{\rm reco}} - p_{D_{\rm meas}}$, where all momenta are measured in the laboratory frame. The m_X resolution is improved by a global $\Upsilon(4S)$ kinematic fit [10] that includes beam position and energy information and constrains the masses and decay vertices of the $D_{\rm meas}$. The χ^2 of this fit is used to reduce the combinatorial background. We remove reconstructed D mesons with χ^2 probability smaller than 0.1%.

Of the selected events, $3-6\%$ ($9-30\%$) contain multiple $D_{(s)}$ ($D^*_{(s)}$) candidates. We retain those in the $D_{\rm meas}$ decay mode with the lowest combinatorial background. If there are multiple candidates with the same decay mode, we select the one with the lowest value of $|m_D - m_{PDG}|$ and $(m_{D_{\rm meas}} - m_{PDG})^2/\sigma^2_{m_{D_{\rm meas}}} + (\Delta m - \Delta m_{PDG})^2/\sigma^2_{\Delta m}$ for $D_{(s)}$ and $D^*_{(s)}$ respectively, where m is the reconstructed mass of the $D_{\rm meas}$ candidate and the subscript PDG indicates nominal values [9].

Finally, we consider only candidates in the range $1.65\,{\rm GeV}/c^2 < m_X < 2.71\,{\rm GeV}/c^2$ for the $D^{(*)+/0}D_X$ modes and $1.68\,{\rm GeV}/c^2 < m_X < 2.31\,{\rm GeV}/c^2$ for $D^{(*)-}_sD_X$. These ranges were chosen to minimize the total uncertainty introduced by the background shape and normalization.

The yield of each decay mode is extracted from the m_X distribution by a binned χ^2 fit of a sum of $n_{\rm sig}$ signal contributions ($N^{\rm sig}$) and the total background contribution ($N^{\rm bkg}$), which is a sum of the combinatorial background, other $B \to D^{(*)}_{(s)}D_X$ decays, and $D^{(*)}_{(s)} - D_{(s)}$ crossfeed, to the experimental data. The signal and background distributions are histograms taken from MC simulation. For D^0D_X we also weight the background shape with a second order polynomial function whose parameters are fitted on data. In the case of $D^{(*)+/0}D_X$ modes we consider three signal components: $D^{(*)+/0}D^-_s$, $D^{(*)+/0}D^{*-}_s$, and $D^{(*)+/0}D_{sJ}(2460)^-$, while in the case of $D^{(*)-}_sD_X$ modes we consider two signal components: $D^{(*)-}_sD^{+/0}$ and $D^{(*)-}_sD^{*+/0}$. The χ^2 is defined as:

$$\chi^2(C_j, C_{\rm bkg}) = \sum_i \left(\frac{N^{\rm meas}_i - \mu_i(C_j, C_{\rm bkg})}{\sqrt{\delta N^{\rm meas2}_i + \delta N^{MC^2}_i}} \right)^2$$

where $N^{\rm meas}_i$ is the number of observed events in bin i, μ_i corresponds to $\mu_i = \sum_{j=1,n_{sig}} C_jN^{\rm sig}_{ij} + C_{\rm bkg}N^{\rm bkg}_i$, the index j denotes the signal component, and $\delta N^{\rm meas}_i$ and δN^{MC}_i are the statistical uncertainties for data and MC samples, respectively. The relative normalizations of each component (C_j and $C_{\rm bkg}$) are allowed to vary in the fit. The measured m_X distributions and the results of the fits are shown in Fig. 2.

The branching fractions are extracted as $\mathcal{B}(f) = N_{\rm fit}/(\varepsilon N_{B_{\rm reco}})$, where $N_{\rm fit}$ is the number of signal events obtained from the fit to the m_X distribution for a given mode and ε, which includes the intermediate branching

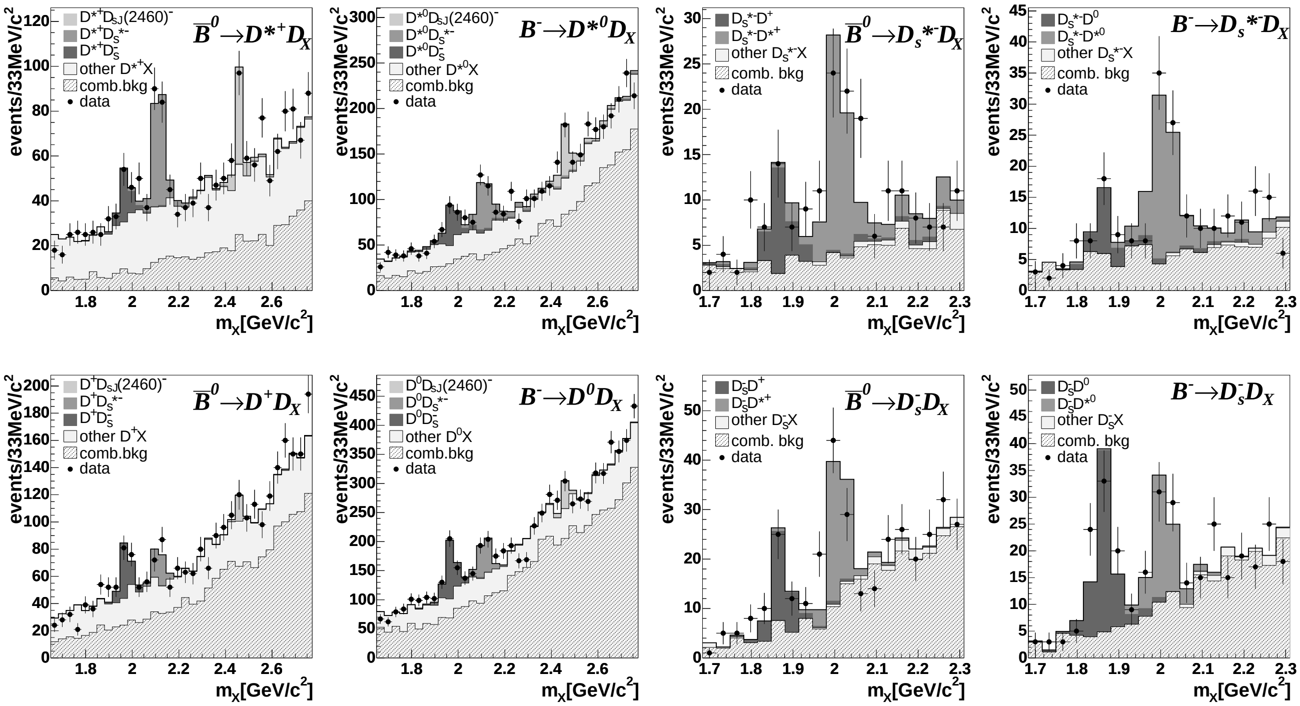

FIG. 2: Distributions of m_X. Fitted $\overline{B} \to D^{(*)+,0} D_s^{(*)-}$ and $\overline{B} \to D^{(*)+,0} D_{sJ}(2460)^-$ signal contributions and background components, determined as described in the text, are overlaid to the data points.

fractions of $D_{\rm meas}$ and its decay products, is the selection efficiency estimated using MC simulation.

The dominant systematic uncertainties originate from the lack of knowledge of the correct shapes used in the m_X fit, and from the determination of efficiencies (because of the limited MC statistics). These uncertainties range from 5.6% to 25%, depending on the mode. The systematic uncertainties due to the determination of $N_{B_{\rm reco}}$ and to the differences between data and MC in the composition of the reconstructed $B_{\rm reco}$ modes range between 3.7% and 6.7% for B^0, and between 3.5% and 9.0% for B^+ depending on the mode under study. Other uncertainties come from track reconstruction efficiency (1.4% per track and 2.2% per soft pion), γ and π^0 efficiencies (3.0% per π^0 and 1.8% per γ), and kaon identification (2% per kaon). The uncertainties due to branching fraction measurements for exclusive $D_{(s)}^{(*)}$ decays [9] contribute between 3.0% and 7.4%, depending on the mode. We check the uncertainties introduced by the χ^2 cut of the kinematic fit by comparing data and MC control samples for $B \to D^{(*)} l\nu$ obtained with all previously mentioned cuts except for the $p^* > 1\,{\rm GeV}/c$ criterion applied. The statistical uncertainty of this comparison is used as the systematic uncertainty (between 0.5% and 2.3%).

We combine the sixteen measurements of $B \to D^{(*)} D_{s(J)}^{(*)}$ to obtain the eight branching fractions for these modes and $\mathcal{B}(D_s^- \to \phi\pi^-)$ in a χ^2 fit. In this combination the ratios $\mathcal{B}(D_s^- \to K^{*0}K^-)/\mathcal{B}(D_s^- \to \phi\pi^-)$ and $\mathcal{B}(D_s^- \to K_S^0 K^-)/\mathcal{B}(D_s^- \to \phi\pi^-)$, included in the efficiency calculation when $D_{\rm meas} = D_s^{(*)-}$, are fixed [9], while $\mathcal{B}(D_s^- \to \phi\pi^-)$ is a free parameter. The MC model used to generate the $D_s^- \to K^+K^-\pi^-$ decays does not include any interference among the different final states ($\phi\pi^-$, $K^{*0}K^-$, $f_0(980)\pi^-$, ...). Correlated and uncorrelated uncertainties are properly taken into account in the covariance matrix. The results of this fit are given in the last column of Table I.

We further combine the results of this analysis with $\overline{B} \to D^{(*)+/0} D_s^{(*)-}$ exclusive branching fractions from [11, 12, 13, 14] and the *BABAR* results for $\mathcal{B}(\overline{B} \to D_{sJ}(2460)^- D^{(*)})$ [4], obtaining the following branching fractions:

$$\mathcal{B}(D_{sJ}(2460)^- \to D_s^{*-}\pi^0) = (56 \pm 13_{\rm stat.} \pm 9_{\rm syst.})\%,$$
$$\mathcal{B}(D_{sJ}(2460)^- \to D_s^-\gamma) = (16 \pm 4_{\rm stat.} \pm 3_{\rm syst.})\%,$$
$$\mathcal{B}(D_s^- \to \phi\pi^-) = (4.62 \pm 0.36_{\rm stat.} \pm 0.50_{\rm syst.})\%.$$

In conclusion, we have measured the branching fractions for the decays $\overline{B} \to D^{(*)+,0} D_s^{(*)-}$. These are consistent with the existing measurements [9] and, in several cases, have a significantly smaller uncertainty. The combination of these results with the existing measurements provide the branching fraction for $D_s^- \to \phi\pi^-$, which is also consistent with the most recent measurement

TABLE I: Event yields ($N_{\rm fit}$), efficiencies (ε), and branching fractions ($\mathcal{B}$) for pairs of detected decay modes, separately and combined. In this combination we use only the results in this paper. $\mathcal{B}(D_s^- \to \phi\pi^-)$ is a free parameter and is also reported in the table. The first uncertainty on $\mathcal{B}$ is statistical, the second is systematic. The parameter k corresponds to $k = 3.6\%/(\mathcal{B}(D_s^- \to \phi\pi^-))$.

Decay mode	$D_{\rm meas}$	$N_{\rm fit}$	$\varepsilon(\%)$	$\mathcal{B}(\%)$	Combined $\mathcal{B}(\%)$
$\overline{B}^0 \to D_s^- D^+$	D^+	86 ± 17	3.29 ± 0.16	$0.90 \pm 0.18 \pm 0.14$	$0.64 \pm 0.13 \pm 0.10$
	D_s^-	39 ± 9	1.79 ± 0.12	$(0.74 \pm 0.17 \pm 0.13) \cdot k$	
$\overline{B}^0 \to D_s^{*-} D^+$	D^+	63 ± 19	3.24 ± 0.16	$0.67 \pm 0.20 \pm 0.11$	$0.69 \pm 0.16 \pm 0.09$
	D_s^{*-}	30 ± 9	0.91 ± 0.08	$(1.15 \pm 0.33 \pm 0.26) \cdot k$	
$\overline{B}^0 \to D_s^- D^{*+}$	D^{*+}	48 ± 13	2.86 ± 0.13	$0.57 \pm 0.16 \pm 0.09$	$0.71 \pm 0.13 \pm 0.09$
	D_s^-	68 ± 12	1.63 ± 0.10	$(1.42 \pm 0.26 \pm 0.20) \cdot k$	
$\overline{B}^0 \to D_s^{*-} D^{*+}$	D^{*+}	129 ± 18	2.68 ± 0.09	$1.65 \pm 0.23 \pm 0.19$	$1.68 \pm 0.21 \pm 0.19$
	D_s^{*-}	84 ± 14	0.86 ± 0.05	$(3.38 \pm 0.60 \pm 0.61) \cdot k$	
$B^- \to D_s^- D^0$	D^0	214 ± 28	3.46 ± 0.11	$1.33 \pm 0.18 \pm 0.32$	$0.92 \pm 0.14 \pm 0.18$
	D_s^-	66 ± 10	1.28 ± 0.07	$(1.11 \pm 0.17 \pm 0.17) \cdot k$	
$B^- \to D_s^{*-} D^0$	D^0	160 ± 31	3.71 ± 0.12	$0.93 \pm 0.18 \pm 0.19$	$0.77 \pm 0.15 \pm 0.13$
	D_s^{*-}	26 ± 10	0.64 ± 0.05	$(0.87 \pm 0.33 \pm 0.16) \cdot k$	
$B^- \to D_s^- D^{*0}$	D^{*0}	152 ± 29	2.69 ± 0.10	$1.21 \pm 0.23 \pm 0.20$	$0.76 \pm 0.15 \pm 0.13$
	D_s^-	52 ± 11	1.33 ± 0.07	$(0.82 \pm 0.18 \pm 0.10) \cdot k$	
$B^- \to D_s^{*-} D^{*0}$	D^{*0}	216 ± 33	2.73 ± 0.07	$1.70 \pm 0.26 \pm 0.24$	$1.62 \pm 0.22 \pm 0.18$
	D_s^{*-}	90 ± 15	0.82 ± 0.04	$(2.38 \pm 0.41 \pm 0.31) \cdot k$	
$D_s^- \to \phi\pi^-$	-	-	-	-	$4.58 \pm 0.48 \pm 0.68$
$\overline{B}^0 \to D_{sJ}(2460)^- D^+$	D^+	27 ± 16	3.61 ± 0.27	$0.26 \pm 0.15 \pm 0.07$	
$\overline{B}^0 \to D_{sJ}(2460)^- D^{*+}$	D^{*+}	64 ± 15	2.51 ± 0.15	$0.88 \pm 0.20 \pm 0.14$	
$B^- \to D_{sJ}(2460)^- D^0$	D^0	75 ± 28	3.78 ± 0.24	$0.43 \pm 0.16 \pm 0.13$	
$B^- \to D_{sJ}(2460)^- D^{*0}$	D^{*0}	147 ± 34	2.81 ± 0.14	$1.12 \pm 0.26 \pm 0.20$	

[15] and confirms a larger value compared to the previous world average [9]. We have extracted the absolute branching fractions for $\overline{B} \to D^{(*)+,0} D_{sJ}(2460)^-$, thus allowing the first measurement of the $D_{sJ}(2460)^-$ decay rates. Our results show that the $D_{sJ}(2460)^-$ meson decays via photon or π^0 emission to $D_s^{(*)-}$ in $(72 \pm 19)\%$ of the cases.

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